

1.7 Semiconductor detectors

1.7.1 Principles of semiconductor detectors.

In a crystal, the atoms are packed so tightly together that the energy states of individual atoms are modified. This modification splits the states into a number of closely spaced energy levels or bands. The top most bands (called the conduction band) have unfilled energy levels. In a conducting solid, the group of "filled bands" are in direct contact with the group of "unfilled bands," so electrons are easily moved into the conduction band (Fig.1.26 (a)).

In a good insulator, there is a large enough gap between the group of filled bands and the group of unfilled bands so that a large amount of energy is required to move an electron to the conduction band (Fig.1.26 (b)).

A semiconductor has a smaller gap between the two groups of bands so that under certain conditions, electrons can be moved to the conduction band. (For example, heating the material will move at least some electrons to the conduction band (Fig.1.26 (c)).

When an electron is moved to a higher band, that is, from valence to conduction, a vacancy occurs in the band which it left. This vacancy is called a hole (Fig.1.26 (d)).

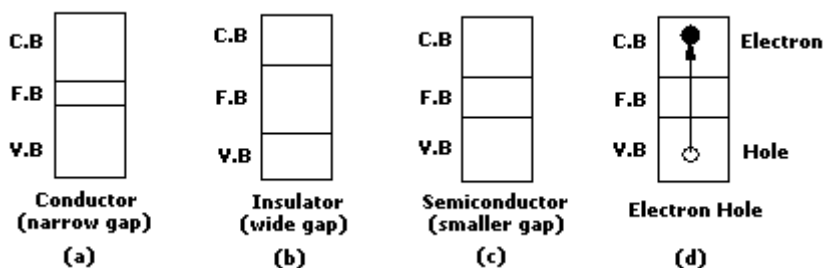


Figure 1.26: conductor, insulator, semiconductor and electron hole [15].

If a strong electric field is applied to the crystal, the electron in the conduction band moves in accordance with the applied field. Similarly, in

the group of filled bands, an electron from a lower energy band moves up to fill the hole (vacancy) in the valence band. The hole it leaves behind is filled by an electron from yet a lower energy band. This process continues, so the net effect is that the hole appears to move down through the energy bands in the filled group. Thus, the electron moves in one direction in the unfilled group of bands, while the hole moves in the opposite direction in the filled group of bands. This can be likened to a line of cars awaiting a toll booth, the toll booth being the forbidden band. As a car leaves the "filled valence band" for the unfilled conduction band, a hole is formed. The next car in line fills this hole, and creates a hole, and so on. Consequently, the hole appears to move back through the line of cars.

Any impurities in the crystalline structure can affect the conducting ability of the crystalline solid. There are always some impurities in a semiconductor, no matter how "pure" it is. However, in the fabrication of semiconductors, impurities are intentionally added under controlled condition. If the impurity added has an excess of outer electrons, it is known as a donor impurity, because the "extra" electron can easily be raised or donated to the conduction band. In effect the presence of this donor impurity decreases the "gap" between the group of filled bands and the group of unfilled bands. Since conduction occurs by the movement of a negative charge, the substance is known as an n-type material. Similarly, if the impurity does not contain enough outer electrons, a vacancy or hole exists. This hole can easily accept electrons from other energy levels in the group of filled bands, and is called an acceptor substance. Although electrons move to fill holes, as described above, the appearance is that the holes move in the opposite direction. Since this

impurity gives the appearance of positive holes moving, it is known as a p-type material.

Since any crystalline material has some impurities in it, a given semiconductor will be an n-type or a p-type depending on which concentration of impurity is higher. If the number of n-type impurities is exactly equal to the number of p-type impurities, the crystalline material is referred to as an "intrinsic semiconductor".

A semiconductor that has been "doped" with the proper amount of the correct type of impurity to make the energy gap between the two groups of bands just right, makes a good radiation detector. A charged particle loses energy by creating electron-hole pairs.

If the semiconductor is connected to an external electrical field, the collection of electron-hole pairs can lead to an induced charge in the external circuit much as the collection of electron-positive atom pairs (ion pairs) is used to measure radiation in an ion chamber. Therefore, the semiconductor detector relies on the collection of electron-hole pairs to produce a usable electrical signal.

One disadvantage of the semiconductor "detector" is that the impurities, in addition to controlling the size of the energy gap also act as traps. As electrons (or holes) move through the crystalline material, they are attracted to the impurity areas or centers because these impurity centers usually have a net charge. The carrier (electron or hole) may be trapped for awhile at the impurity center and then released. As it begins to move again, it may be trapped at another impurity center and then released again if the electron or hole is delayed long enough during transit through the crystal, it may not add to the electrical output.

Thus, although the carrier is not actually lost, the net effect on readout is that it is lost. Another disadvantage of the semiconductor detector is that the presence of impurities in the crystal is hard to control to keep the energy gap where it is desired a newer technique, the junction counter, has been developed to overcome these disadvantages.

In a semiconductor junction counter, an n-type substance is united with a p-type substance (Fig.1.27). When the two are diffused together to make a diffused junction, a depletion layer is created between the two materials. (This depletion layer is formed by the diffusion of electrons from the n-type material into the p-type material and the diffusion of holes from the p-type material into the n-type material.) This results in a depleted of carriers and which behaves like an insulator bounded by conducting electrodes. That is, a net charge on each side of the depletion region impedes the further transfer of charge. This charge is positive in the n-region and negative in the p-region. This barrier can be broken if we apply an external voltage to the system and apply it with the proper bias. A "forward bias" is applied when we connect the positive electrode to the p-region. In this case, the barrier breaks down and electrons flow across the junction. However, if we apply a "reverse bias"(negative electrode connected to the p-region), the barrier height is increased and depleted region is extended.

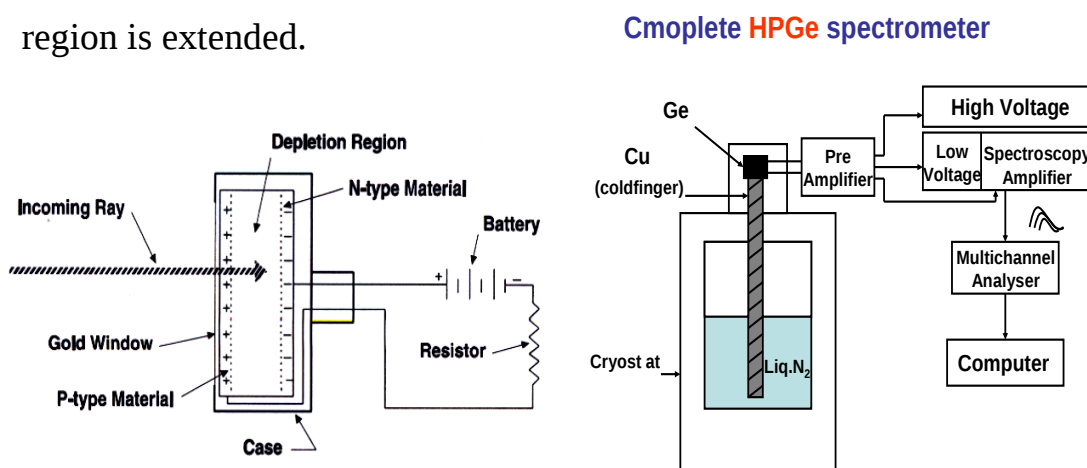


Figure 1.27: semiconductor junction counter [12].

A further advancement in junction counters is the p-n type. This counter has an intrinsic region between the n and p surface layers. (An intrinsic semiconductor was discussed earlier and is effectively a pure semiconductor.) The presence of an intrinsic region effectively creates a thicker depletion area. A Ge(Li) detector is an example of this type of detector.

Lithium (an n-type material) is diffused into p-type germanium. The n-p junction that results is put under reverse bias, and the temperature of the material is raised. Under these conditions, the lithium ions drift through the germanium, balancing n and p material and forming an intrinsic region.

The heat and bias are removed and the crystal cooled quickly to liquid nitrogen temperatures. This intrinsic region serves as the region in which interactions can take place. The intrinsic region can be thought of as a built-depletion region.

Due to the large size of the depletion region and the reduced mobility of the electrons and holes due to the depressed temperature, a high charge is necessary to cause conduction. The charge is chosen high enough to collect ion pairs, but low enough to prevent noise.

Due to the increased stopping power of germanium over air at -321°F the energy required to create an ion pair is only 2.96 eV compared to 33.7 eV for air. This means that by theory, a germanium detector will respond to any radiation that will create ion pairs. In actuality, however, the response to radiations other than gamma is limited by the materials surrounding the detector, material necessary to maintain temperature. Another consideration limiting response is the geometry of the crystal. The most efficient response occurs when the interaction takes place in the center of the intrinsic region, this can only occur for gamma.

Radiation interacts with atoms in the intrinsic region to produce electron hole pairs. The presence of ion pairs in the depletion region causes current flow. This is similar to transistor, in that instead of inducing charges in the center section (the base in a transistor) by a battery or an other source, the charge is induced by the creation of ion pairs. Since it is not necessary for the ion produced to reach the p and n region to be collected, as in a gas filled chamber, the response is faster.

Since the number of ion pairs produced is a function of the incident energy, and the resulting current is a function of the amount of ion pairs, Ge(Li) response is in terms of energy [15].

1.8. Ge(Li) systems.

A typical Ge(Li) detector system consists of a vacuum enclosed Ge(Li) crystal which is coaxial in shape and attached to a copper cold finger through an agate insulator .the crystal is under a vacuum to prevent frost forming on the crystal , and damage caused by impurities in the air. The cold finger is immersed in liquid nitrogen in a Dewar (-196°C).The crystal is subject to failure should its temperature be raised to room temperature due to lithium ion drift and increased electron noise [15].

1.8.1. Advantages of Ge(Li) detectors.

Ge(Li) detectors offer an advantage of high resolution (i.e. the ability to differentiate between closely adjacent gamma photopeaks. It can resolve the three photopeaks of $^{95}\text{Zr/Nb}$ whereas this would appear as one photopeak with NaI(Tl) detectors. Ge(Li) also has a short response time and a more linear energy response than NaI(Tl). Small size crystals offer the best resolution but the efficiency of detection is lowered [15].

1.8.2. Disadvantages of Ge(Li) detectors.

Ge(Li) systems can only be used for gamma photon detection .a cryogenic (liquid nitrogen) system is required to cool the detector and this adds to the initial cost as well as a continuing operation cost. Because detectors are presently limited to less than 100-300 cc in size, the efficiency of counting is low compared to NaI. Counting times in excess of 1,000 minutes are necessary for environmental samples [15].

1.8.3. Intrinsic germanium detectors.

One of the major disadvantages of Ge(Li) detectors is the requirement that the crystal must always be kept cooled by liquid nitrogen. If the detector is ever allowed to reach room temperature, the lithium ions will drift and an effective intrinsic depletion region (the area of electron-hole pair formation) will no longer exist. The detector can be returned to the manufacturer for redrifting, but the process is expensive and time consuming. The detector may be less efficient than before the redrifting. The bulky size of the liquid nitrogen Dewar also places imitations on the uses of a Ge(Li) detector .a semiconductor detector that could be operated and /or stored at room temperature would have advantages for use in installed effluent monitors or portable units [15].

1.9. Hyper pure germanium (HPGe) detector.

In natural germanium of normal purity, the depletion region is only a few millimeters thick .the crystal is, in effect, a conductor due to the impurities in the crystal. Resistance is very low in the crystal, and detected electron flow (noise) may be caused by conditions other than radiation (e.g., heat). As a result, the natural crystal is virtually useless for radiation detection.

The use of the lithium drifting process in GeLi detectors creates an artificial depletion /intrinsic zone of 10-15 mm. the Ge(Li) detector is a semiconductor. The resistance is greater than the resistance for a natural germanium crystal, and by applying the correct voltage to the crystal, most non-radiation events that induce electron flow can be eliminated. Ge(Li) detectors are used in radiation detection; however, the crystal must be maintained at the temperature of liquid nitrogen to maintain the depletion intrinsic zone.

If an extremely pure germanium crystal is created, the crystal's resistance will be sufficiently big so that a depletion region of 10mm can be obtained by using a reverse bias voltage, instead of drifting lithium through the germanium as is done in Ge(Li) detectors. This pure germanium crystal would have, like Ge(Li) crystals ,semiconductor properties , and by applying the correct voltage could be used to collect electrons induced by radiation . Recently, processes for creating germanium in a very high state of purity have been developed. This, in turn, has led to the development of a semiconductor that can be stored at room temperature. The pure germanium crystals are usually called "intrinsic germanium" or "high purity germanium" (abbreviated HPGe) detectors. HPGe crystals are perhaps the most highly purified material that has even been produced.

Note that in the above paragraph it was stated that the HPGe crystals could be stored at room temperature. This is because HPGe crystals are not lithium drifted. However, there was no mention of operating detectors with the crystals at room temperature. In order to reduce unwanted detector noise (caused by reduced resistance at room temperature) the

detector must be operated at the temperature of liquid nitrogen. Experience has shown that the crystals can be cycled between room and cold temperatures without damage. Most manufacturers, however, recommend that the detectors be continuously maintained at liquid nitrogen temperatures if possible, only difference between Ge(Li) and HPGe in principle of operation [15].

1.9.1. Advantages of HPGe's.

The Dewar used for storing the liquid nitrogen coolant for HPGe detectors can be smaller than the Dewar used for Ge(Li) detectors. HPGe detectors are more portable. The main advantage is that should the detector be allowed to rise to room temperature (with no voltage applied) the detector need only be returned to and stabilized at liquid nitrogen temperatures to be used [15].

1.9.2. Disadvantages of HPGe's.

Even though the Dewar is smaller for the HPGe detector they still require liquid nitrogen cooling and tend to be fairly expensive [15].

1.9.3. High purity germanium (HPGe) detector fabrication.

This material, already of high purity, is further processed using the technique of zone refining. The impurity levels are progressively reduced by locally heating the material and slowly passing a melted zone from one end of the sample to the other. Since impurities tend to be more soluble in the molten germanium than in the solid, impurities are preferentially transferred to the molten zone and are swept from the sample .after many repetitions of this process.

The resulting germanium is perhaps the most highly purified and completely analyzed material of any kind that has ever been produced in commercial volume.

If the remaining low-level impurities are acceptors (such as aluminum) the electrical properties of the semiconductor crystal grown from the material is mildly p-type. (The designation π type is often used to represent this high-purity p-type material.). Alternatively, if donor impurities remain, high-purity n-type (designated ν type) is the result [4].

1.9.4. Planar configuration.

For a planar detector (Fig.1.28), a slice of high-purity germanium is diffused with the donor lithium on one side, forming a strongly n-type layer. The opposite side is implanted with the acceptor boron, forming a p-layer. When voltage is properly applied, the electric field direction prevents the majority carriers in the contact regions from being injected across the device. As the voltage is applied, a region depleted of holes will advance into the slice from the n^+ contact if the slice is p-type. If the slice is n-type, a region depleted of electrons will advance from the p^+ contact [4].

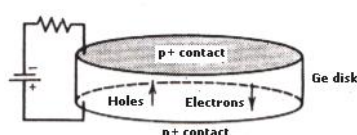


Figure 1.28: configuration of a planar HPGe detector [4].

1.9.5. Coaxial configuration.

The detector is then constructed in cylindrical or coaxial geometry as illustrated in (Fig.1.29).

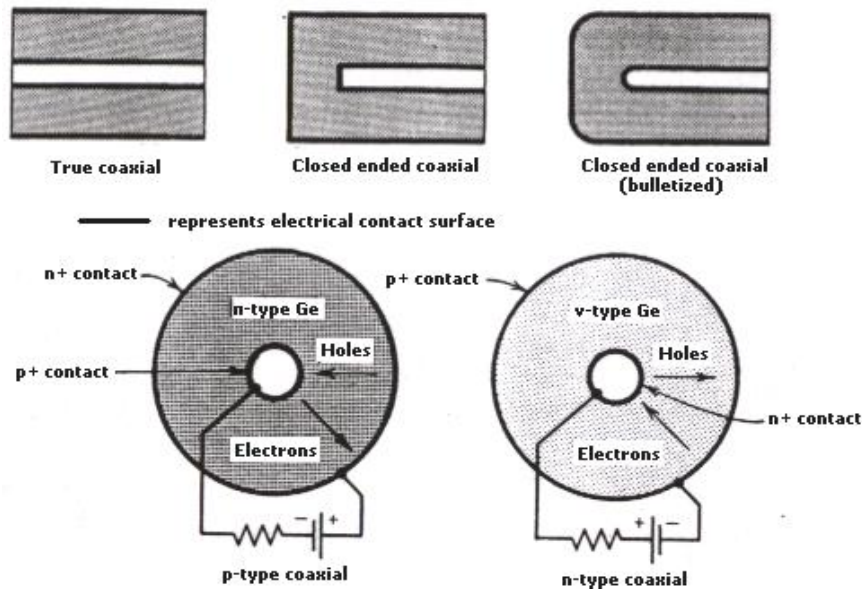


Figure 1.29: At the top are shown the three common shapes of large volume coaxial detectors. each represents a cross sectional view through the axis of a cylindrical crystal. The outer electrode is extended over the flat front (left) surface in both closed ended cases. Cross sections perpendicular to the cylindrical axis of the crystal are shown at the bottom. The HPGe material may be either high purity p or n type. The corresponding electrode configurations are shown for each type [4].

In this case, one electrode is fabricated at the outer cylindrical surface of a long germanium cylindrical crystal. A second cylindrical contact is provided by removing the core of the crystal and placing a contact over the inner cylindrical surface .because the crystal can be made long in the axial direction, much larger active volumes can be produced .An added advantage of coaxial geometry is that, by using a small inner diameter, large-volume detectors can be fabricated with lower capacitance than would be possible using planar geometry [4].